Subcarrier, Bit and Time Slot Allocation for Multicast Precoded OFDM Systems

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***Abstract*—The conventional resource allocation method in multicast OFDM systems adapts the physical layer to the worst user link conditions. In this paper, we propose new subcarrier, bit and time slot allocation algorithms for multicast OFDM systems in indoor powerline communication (PLC) context. To increase the multicast bit rate, these algorithms jointly use linear precoded OFDM (LP-OFDM) modulation technique and the conventional multicast approach to exploit the channel frequency selectivity experienced by each user. The LP technique applied to OFDM systems has already proved its ability to significantly increase the system throughput in a PLC context. Here, different groups of multicast users according to their channel conditions are created and different ways of gathering users, leading to different modes, are analyzed. Simulations are run over indoor PLC channels and it is shown that the proposed modes combined with the LP-OFDM solution offer a significant bit rate gain compared to the conventional multicast approach. In addition, the interest of gathering multicast users into groups for multicast OFDM systems in PLC context is shown.**

I. Introduction

Multicasting is a network addressing method for the delivery of data to a group of users simultaneously using less network resources. For multimedia applications, this technique offers a significant improvement compared to unicasting. Multicast routing is a well-investigated subject in the literature [1]. In this paper, we address the adaptation of the physical (PHY) layer parameters for multicast OFDM systems in indoor powerline communication (PLC) context. Since indoor PLC are being used to deliver triple play services, the multicast may be interesting in this case. Over the PHY layer, resources have to be allocated in order to satisfy requirements of each multicast user. Yet, the difference in link conditions of users makes it difficult to adapt the PHY layer (coding rate, modulation index, etc.) to the link conditions of each user. The conventional resource allocation method in multicast orthogonal frequency division multiplexing (OFDM) adapts the PHY layer to the worst user link conditions. Consequently, the final multicast bit rate is limited by the worst user channel conditions and all users receive the same bit rate [2].

To increase the total multicast bit rate, it has been suggested to separate users in frequency domain by exploiting hierarchy in multicast data [2], [3], [4]. When employing multi-resolution coding, the multicast data is compressed into a number of layers, arranged in a hierarchy which provides progressive refinement. Then, for OFDM systems, each subcarrier is assigned to a group of users which receive the same data symbols on this subcarrier. And the number of loaded bits on each subcarrier is determined considering the lowest one among the channel amplitudes of all the users sharing this subcarrier.

In PLC context, the powerline channel exhibits multipaths caused by reflections on the discontinuities of the network, and the link conditions can be very poor. Few studies have been carried out on multicast OFDM systems for PLC, and even lesser studies seeking to increase the multicast bit rate without using hierarchical data.

In this paper, we propose new resource allocation algorithms for multicast OFDM systems in order to increase the bit rate. These algorithms jointly use the linear precoded OFDM (LP-OFDM) modulation and the conventional resource allocation scheme in multicast systems to exploit the channel frequency selectivity experienced by each user. LP-OFDM is a combination of multicarrier and spread spectrum techniques also known as MC-SS techniques. This technique has shown very good performances in difficult environments and brings a significant increase in bit rate compared to conventional OFDM systems [5], [6]. Due to power spectral density (PSD) constraint in PLC systems, all users have the same peak power constraint on each subcarrier and there is no power allocation. In addition, to increase the total multicast bit rate and to reduce the impact of the worst user channel conditions, we propose to gather multicast users into groups according to their channel conditions. We allocate one different time slot to each group and three modes of gathering multicast users are presented and analyzed.

This paper is organized as follow. Section II introduces the resource allocation in multicast OFDM systems and section III presents the optimization problem for multicast LP-OFDM systems in PLC context. Section IV describes the proposed solutions to this optimization problem and section V presents the three modes of gathering multicast users into groups. The performances of these solutions are given in section VI over PLC channels. Finally, section VII concludes the paper.

II. Resource Allocation in Multicast OFDM Systems

Multicast delivers data to a group of users by a single transmission, which is particularly useful for high-data-rate multimedia service due to its ability to save the network resources [2]. In PLC systems, a feedback path from each user to the transmitter reports the channel conditions.In multicast OFDM systems and in non-hierarchical data context, the modulation should be adjusted to serve all users and especially the user with the worst channel conditions. The conventional method in multicast OFDM, LCG (low channel gain, [4]), consists in allocating resources while satisfying requirements of all users. This method adapts the PHY layer to the worst user link conditions and sets the number of loaded bits per subcarrier with the lowest number of loaded bits over this subcarrier, considering all the channels of users. Hence, the total loaded bits with LCG method in PLC context writes

$$\mathcal{R}^{\mathrm{LCG}} = \sum_{n=1}^{N} \mathcal{R}_n^{\mathrm{LCG}} = \sum_{n=1}^{N} \left(\min_u \log_2 (1 + \frac{E}{\Gamma N_0} |H_{u,n}|^2) \right) , \tag{1}$$

where $|H_{u,n}|^2$ is the channel amplitude of user u on subcarrier n, E is the PSD constraint, Γ is the signal-to-noise ratio (SNR) gap, N_0 is the background noise level. It is obvious to show that the multicast bit rate offered by this LCG method decreases when the number of users increases, as

$$\min_{1 \leq u \leq U} f(u) \geq \min_{1 \leq u \leq U+1} f(u) \tag{2}$$

for any function f. It has been shown in [4] that the multicast capacity is saturated as the number of users increases due to the different channel selectivity.

III. Adaptive bit rate maximization in multicast LP-OFDM systems

In this paper, we jointly use LP-OFDM modulation techniques and LCG method to exploit the channel frequency selectivity experienced by each user. As previously stated, LP-OFDM results from the combination of multicarrier modulation and spread spectrum. The LP technique consists in connecting a set of subcarriers with precoding sequences to exploit mutually their energies [5]. This set of subcarriers will be called block and the subcarriers in one block are not necessary adjacent. The number of blocks is the ratio of total number of subcarriers N to the precoding sequence length L. We assume the same precoding sequence length L for all blocks. If judiciously done, each resulting set holds an equivalent signal-to-noise ratio (SNR) such that the total supported throughput is greater than the sum of the individual throughputs supported by each subcarrier taken separately. Compared to the conventional OFDM systems, the linear precoding matrix, which is an orthogonal Hadamard matrix is added [6]. As a result, the proposed multicast LP-OFDM systems work with blocks of subcarriers connected by precoding sequences.

The following expressions for LP-OFDM modulation are derived from [5], [6].The optimum achieved bit rate of the LP-OFDM system using ZF detection writes

$$\mathcal{R}_{u,b} = L \log_2 \left(1 + \frac{1}{\Gamma} \frac{L}{\displaystyle\sum_{n \in S_b} \frac{1}{|H_{u,n}|^2}} \frac{E}{N_0} \right) , \tag{3}$$

where S_b is the set of subcarriers within the bth block. The conventional OFDM system is obtained for $L = 1$.

To maximize the bit rate $\mathcal{R}_{u,b}$ given by (3), it suffices to minimize the sum $\sum_{n \in S_b} \frac{1}{|H_{u,n}|^2}$. This corresponds to choose the subcarriers with best channel amplitudes $|H_{u,n}|^2$. A simpler solution is to sort subcarriers in descending order and to choose the first L subcarriers.

In multicast systems, when considering the LP-OFDM modulation, the loaded bits over the block S_b of subcarriers will be the lowest bit rate of users over this block. This number of loaded bits writes

$$\mathcal{R}_b^{\mathrm{LP}} = \min_u \mathcal{R}_{u,b} \,. \tag{4}$$

Due to the PSD constraint in PLC systems, all users have the same peak power constraint E on each subcarrier. Hence, there is no power allocation. For simplicity, it is assumed that all users utilize the same precoding sequence length L for all blocks.

The optimization problem writes

$$\max_S \sum_{b=1}^{B} \mathcal{R}_b^{\mathrm{LP}} = \max_S \sum_{b=1}^{B} \left(\min_u \quad \mathcal{R}_{u,b} \right) , \tag{5}$$

where $S = \{S_1, S_2, \cdots S_B\}$ is the set of different blocks. This is a combinatorial and min-max-sum resource allocation problem, which is NP-hard [7]. We need to find the optimal S, which maximizes the multicast bit rate. Since this problem of repartition of subcarriers into blocks does not have analytical solution, algorithmic solutions are proposed in the following.

IV. Proposed solutions to the optimization problem

A. Optimal solution: combinatorial solution

The basic resolution for finding the optimal block of subcarriers is to test all possibilities of gathering subcarriers in blocks and then to choose the best case. Looking for all possibilities is a combinatorial problem. As both the order of subcarrier indexes within a block and the order of blocks do not change the result, the number of possibilities writes

$$\frac{\binom{N}{L} \times \binom{N-L}{L} \times \binom{N-2L}{L} \times \ldots \times \binom{2L}{L}}{(\frac{N}{L})!} = \frac{N!}{(L!)^{(\frac{N}{L})} (\frac{N}{L})!} , \tag{6}$$

where the number N of subcarriers is multiple of the number L of subcarriers per block. This number of possibilities depicts the number of combinations of L out of N, and the number of combinations of L out of $N - L$, until all combinations are taken into account. Then, the total number of combinations is divided by the number of arrangements of blocks.

For a fix precoding sequence length, this solution gives the optimum multicast bit rate, but becomes unfeasible when the number of subcarriers increases. In this paper, we propose simplified resource allocation algorithm for PLC scenarios. These algorithms jointly use LP-OFDM modulation techniques and LCG algorithm to exploit the channel frequency selectivity experienced by each multicast user.

B. Exploitation of the equivalent channel

Here, we define an equivalent channel, which is the combination of channel conditions of different users. Actually, for each index of subcarrier, the equivalent amplitude of the channel is given by the amplitude of the worst user subcarrier. Let $\left|H_n^{\text{eq}}\right|^2$ be the equivalent multicast channel amplitude on subcarrier n. Hence,

$$\left|H_n^{\text{eq}}\right|^2 = \min_u \left|H_{u,n}\right|^2 . \tag{7}$$

Computing this equivalent multicast channel, the multicast resource allocation is the same as the single link resource allocation. Bit-loading algorithms, as proposed in [8] for single user context, can then be applied to this equivalent channel. The LCG method gives results for the conventional OFDM bit loading algorithm ($\mathcal{R}_n^{\text{LCG}} = \log_2(1 + \frac{E}{\Gamma N_0}\left|H_n^{\text{eq}}\right|^2)$).

To increase the bit rate of this LCG method, we propose to apply the LP-OFDM bit loading in single user context on the equivalent channel and this method will be considered as linear precoding based LCG (LP-LCG) method. Therefore, we sort subcarriers of the equivalent channel in descending order and we gather best available subcarriers in a block.

C. Proposed LBCG (Low Block Channel Gain) method

With this method, we propose to define the different blocks of subcarriers using the equivalent channel before choosing the worst user on each block. This procedure, called LBCG, is the opposite of LP-LCG method where the blocks are defined after the selection of the worst user subcarriers.

The proposed LBCG method leads to better bit rate than the LP-LCG method. Actually, considering blocks of subcarriers, we show, for all $n \in S_b$ and for all u,

$$\begin{aligned}
&\left|H_{u,n}\right|^2 \geq \left|H_n^{\text{eq}}\right|^2 \;\Leftrightarrow\; \sum_{n\in S_b} \frac{1}{\left|H_{u,n}\right|^2} \leq \sum_{n\in S_b} \frac{1}{\left|H_n^{\text{eq}}\right|^2} \\
&\Leftrightarrow\; \mathcal{R}_{u,b} \geq L\,\log_2\left(1 + \frac{E}{\Gamma N_0}\frac{L}{\displaystyle\sum_{n\in S_b}\frac{1}{\left|H_n^{\text{eq}}\right|^2}}\right), \forall u\,, S_b \\
&\Leftrightarrow\; \min_u \mathcal{R}_{u,b} \geq L\,\log_2\left(1 + \frac{E}{\Gamma N_0}\frac{L}{\displaystyle\sum_{n\in S_b}\frac{1}{\left|H_n^{\text{eq}}\right|^2}}\right), \forall S_b \\
&\Leftrightarrow\; \sum_{b=1}^{B}\left(\min_u \mathcal{R}_{u,b}\right) \geq L\sum_{b=1}^{B}\log_2\left(1 + \frac{E}{\Gamma N_0}\frac{L}{\displaystyle\sum_{n\in S_b}\frac{1}{\left|H_n^{\text{eq}}\right|^2}}\right).
\end{aligned} \tag{8}$$

From (8), we derived that the multicast bit rate is bounded. We aim at maximizing the left hand side of inequality (8) according to (5). Maximizing the right hand side of the inequality increases the left hand side and using the best available L subcarriers of the equivalent channel to form S_b maximizes the right hand side. The maximum of the right hand side corresponds to the LP-LCG method. Then, we can derive that the proposed LBCG method is not optimal, but gives better results than the LP-LCG method. Algorithm 1 describes how to compute the multicast bit rate with the LBCG method. Results for the conventional LCG method is obtained for $L = 1$.

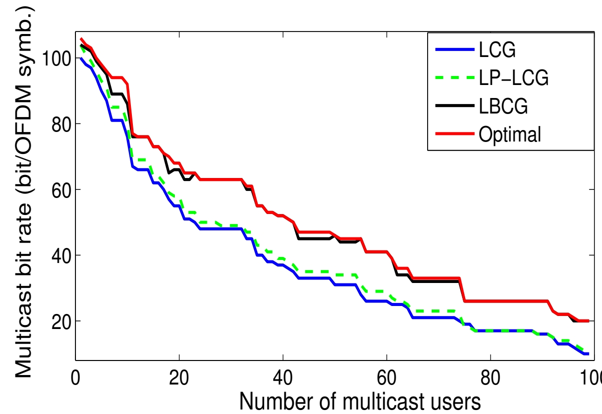

Fig. 1. Total loaded bits per user according to the number of multicast users

Algorithm 1: LBCG algorithm

Data: N, U, B , L, $\left|H_{u,n}\right|^2$ $\forall u, n$
Result: R bit rate per user

begin
  $R \leftarrow 0$;
  for *all subcarrier* n, $n \in [1; N]$ **do**
    compute $\left|H_n^{\text{eq}}\right|^2$ from (7) ;
  sort $\left|H_n^{\text{eq}}\right|^2$ in descending order; let I be the set of sorted indexes;
  for *all block* b, $b \in [1; B]$ **do**
    $S_b \leftarrow I((b-1)L : bL)$;
    for *all user* u, $u \in [1; U]$ **do**
      compute $\mathcal{R}_{u,b}$ from (3) ;
    $\mathcal{R}_b^{\text{LP}} \leftarrow \min_u \mathcal{R}_{u,b}$;
    $R \leftarrow R + \mathcal{R}_b^{\text{LP}}$;
end

D. Comparison of the different methods

In this part, we address the comparison of the different methods over an i.i.d. Rayleigh fading channel. The total number of subcarriers is $N = 12$ and the precoding sequence length is $L = 4$. Fig. 1 shows the multicast bit rate in bit per OFDM symbol. As expected, the optimal solution outperforms the others and the LP component improves the conventional multicast OFDM system (LCG). The LBCG method gives better results than LP-LCG and LCG methods. This method offers performance close to the optimal one which does an exhaustive search of the optimal repartition of subcarriers.

Compared to the conventional LCG method, the additional complexity brought by the LP-LCG method is the utilization of the precoding matrix which is composed of Hadamard

TABLE I
CHANNEL TRANSFER FUNCTION MODEL AND AVERAGE CHANNEL AMPLITUDE BY CLASS.

Class	Channel model, $f \in [2;28]$ MHz	Average channel gain
1	$-80+30\times\cos\left(\frac{f}{5.5\cdot10^7}-0.5\right)$	-52.04 dB
2	$-43+25\times\exp\left(-\frac{f}{3\cdot10^6}\right)-\frac{15}{10^8}f$	-44.35 dB
3	$-38+25\times\exp\left(-\frac{f}{3\cdot10^6}\right)-\frac{14}{10^8}f$	-38.47 dB
4	$-32+20\times\exp\left(-\frac{f}{3\cdot10^6}\right)-\frac{15}{10^8}f$	-33.01 dB
5	$-27+17\times\exp\left(-\frac{f}{3\cdot10^6}\right)-\frac{15}{10^8}f$	-26.45 dB
6	$-38+17\times\cos\left(\frac{f}{7\cdot10^7}\right)$	-21.82 dB
7	$-32+17\times\cos\left(\frac{f}{7\cdot10^7}\right)$	-15.42 dB
8	$-20+9\times\cos\left(\frac{f}{7\cdot10^7}\right)$	-12.30 dB
9	$-13+17\times\cos\left(\frac{f}{4.5\cdot10^7}-0.5\right)$	-6.11 dB

orthogonal matrices. The LBCG method also needs the computation of different $\mathcal{R}_{u,b}$. The additional complexity is marginal compared to the initial complexity.

Note that all users share the same resources and have the same bit rate with these methods. Although the LBCG method significantly increases the conventional multicast bit rate, the multicast bit rate depends on worst user channel conditions. In the $[2;28]$ MHz frequency band, the average PLC channel gains are very different and any combination of these channels for resource allocation in multicast OFDM system may lead to performance limited by the worst class channel. In [9], authors gathered the measured PLC channels in indoor networks into 9 classes according to their capacities, and a model of transfer function is associated to each class. The higher is the channel class number, the better is the channel magnitudes. Table I gives the transfer function models of channels and the average channel gain by class. And Fig. 2 some examples of transfer functions for three classes (class 2, class 5 and class 9) of channels generated in the $[2;28]$ MHz band.

V. PROPOSED SOLUTION TO SEPARATE USERS IN TIME DOMAIN

In this paper, we propose to separate multicast users in time domain in order to reduce the impact of the worst user channel conditions. Hence, we gather multicast users into groups according to their channel conditions (classes). In contrast to previous methods (LBCG, LP-LCG and LCG) where all multicast users share the same time slots, we allocate each time slot to a group of multicast users and each user is part of only one group.

In [2], [4], multicast users are separated in frequency domain in order to increase the total multicast bit rate. Actually,

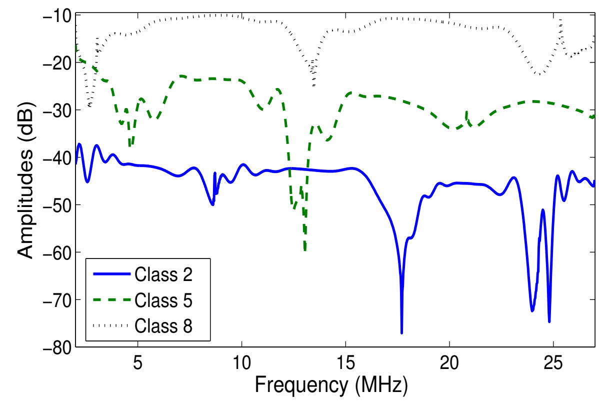

Fig. 2. Examples of transfer functions for three classes (class 2, class 5 and class 9) of channels

each subcarrier is assigned to a group of users which receive the same data symbols on this subcarrier. And then, the number of loaded bits on each subcarrier is determined considering the lowest one among the channel amplitudes of all the users allocated to this subcarrier. In the following, we consider this method as the hierarchical multicast data method (HDM). This method significantly increases the total multicast bit rate compared to the conventional LCG method in wireless communications [2], [4]. But, when channels of users are very different (e.g. mean amplitudes), the algorithm yields a good sum bit rate without assigning any subcarrier to a given user.

A. Analysis of multicast bit rate between two PLC channel classes

In this section, we analyze by simulation the multicast bit rate (in bit per OFDM symbol) of two users, where each user experiences one different class of channel within the 9 classes. We consider only the bit rate offered by LBCG method which gives the best results. Fig. 3 shows the comparison of multicast bit rates for all couples of channel classes. The gaps among these multicast bit rate is proportional to the gaps among the average channel gains of channel classes. These results confirm the fact that the multicast bit rate is limited by the least capable user. In addition, these results suggest that multicast users must be separated so that the worst user does not alter the multicast bit rate. The bit saturation explains the lower gaps among class 7, 8 and 9 cross-bit rates. Actually, 10 bit are assigned to each subcarrier, the best allowed by the HomePlug AV standard.

Based on this analysis, we propose empirical repartition of users taking into account the gaps among the average channel gains and the multicast bit rates between two channel classes. Therefore, we consider three different modes and we use the LBCG method as the resource allocation scheme.

1) Mode 1: 1 group (G1) for all multicast users and all users share the same time slot.
2) Mode 2: 2 groups of multicast users use 2 time slots. Group 1 (G1) is composed of class 1, 2, 3 and 4

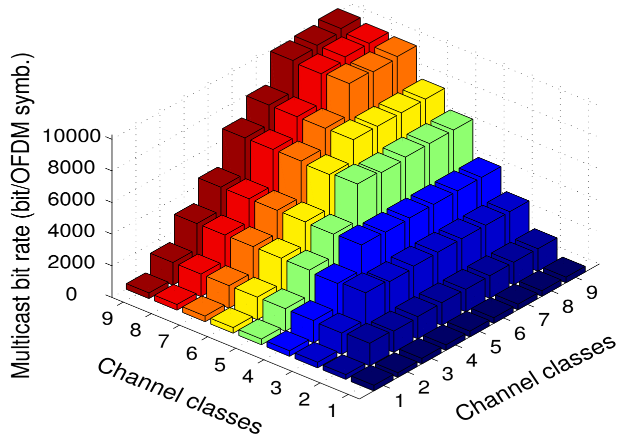

Fig. 3. Comparison of multicast bit rate, in bit per OFDM symbol, between two channel classes

TABLE II
UTILIZATION OF TIME SLOTS BY GROUPS OF MULTICAST USERS ACCORDING TO THE MODE 1, 2 AND 3.

Time slots	1	2	3	4	5	6
Mode 1	G1	G1	G1	G1	G1	G1
Mode 2	G1	G2	G1	G2	G1	G2
Mode 3	G1	G2	G3	G1	G2	G3

channels; and group 2 (G2) is composed of class 5, 6, 7, 8 and 9 channels.

3) Mode 3: 3 groups of multicast users use 3 time slots. Group 1 (G1) is composed of class 1, 2, 3 and 4 channels; group 2 (G2) is composed of class 5 and 6 channels; and group 3 (G3) is composed of class 7, 8 and 9 channels.

Table II gives the repartition of the different groups of multicast users over 6 time slots according to the modes.

VI. SIMULATION RESULTS

In this section, we present simulation results for the proposed LBCG method in different modes applied to multicast systems. The performances of the different algorithms are compared with the conventional multicast approach LCG. The generated signal is composed of $N = 1024$ subcarriers transmitted in the $[2; 28]$ MHz band and the precoding sequence length is $L = 32$. Perfect synchronization and channel estimation are assumed. Furthermore, we assume that the TDMA region for indoor PLC network has been optimized and the optimal time slot duration in a multiuser scenario has been determined for various amounts of overhead required by the PHY layer [10]. A high background noise level of -110 dBm/Hz is considered and the signal is transmitted with respect to a flat PSD of -50 dBm/Hz for all users. Results are given for a fixed target symbol error rate (SER) of 10^{-3} and the system margin is set to 6 dB as in HomePlug AV. The maximum number of bits per symbol is limited to 10. The multipath channel model for PLC proposed in [9] is used.

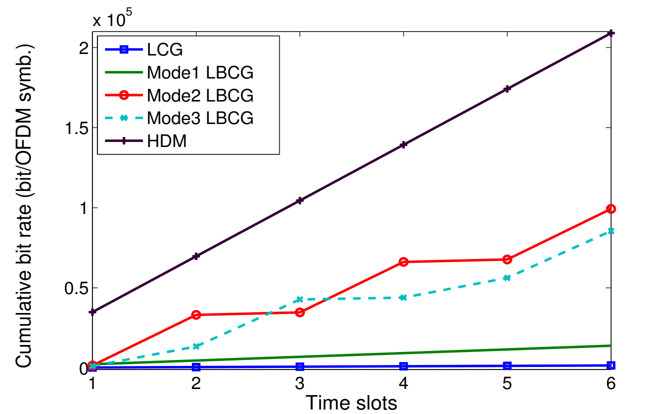

Fig. 4. Comparison of different total bit rate, in bit per OFDM symbol, in different modes with 9 users.

TABLE III
TOTAL BIT RATE, IN BIT PER OFDM SYMBOL, RECEIVED BY USERS OVER 6 TIME SLOTS.

User	1, 2, 3	4	5	6	7	8	9
LCG	258	258	258	258	258	258	258
Mode1 LBCG	2310	2310	2310	2310	2310	2310	2310
Mode2 LBCG	1164	1164	18933	18933	18933	18933	18933
Mode3 LBCG	776	776	12628	12628	19548	19548	19548
HDM	0	3210	13182	46206	48822	48822	48822

In a first step, we consider a multicast system with 9 users and each user experiences one different class of channel within the 9 classes. Fig. 4 shows the cumulative bit rate for 6 time slots (which is sufficient to compare different modes and methods). Whatever the mode used, the LBCG method outperforms the conventional LCG method. With the LBCG method in mode 1, as with the LCG method, all users receive the same bit rate (c.f. table III) whatever their channel conditions. These bit rates remain relatively low. In mode 2 and 3, users with good channel conditions receive more bits and this leads to increase the cumulative bit rates. The mode 2 (2 groups of multicast users) offers more bit rate than mode 3 because in this mode, different group of users transmit data in one more time slot. In addition, the hierarchical multicast data (HDM) method offers the best cumulative bit rates compared to other methods. But, Table III shows that user 1, user 2 and user 3 do not receive any bit rate because of their bad channel conditions. These results suggest that when the mean channel gains are very different, users with bad channel conditions are not served. In this case, the multicast is not ensured. Over PLC channels, where the mean channel gains are different, the HDM method is not able to perform multicasting.

In a second step, we present results of different modes with the LBCG method compared to the conventional LCG method when the number of multicast users increases. The HDM method is not performed because it is not able to serve

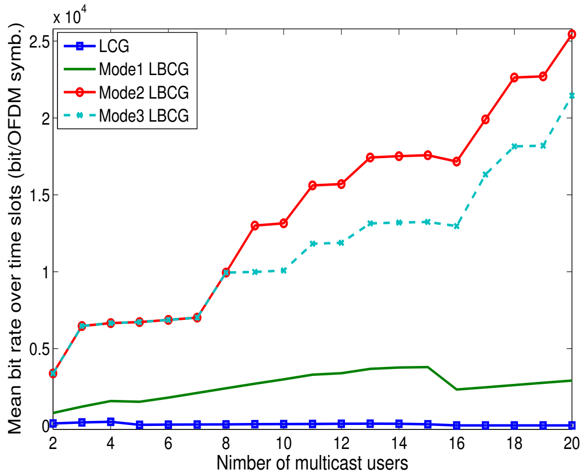

Fig. 5. Comparison of different bit rates in different modes when the number of multicast users increases.

all the multicast users. The number of multicast users varies from 2 to 20 and each user randomly experiences one class of channel. Figure 5 shows the mean bit rates over the number of time slots used and this number of used time slots depends on the mode and the number of active groups (mode 1 uses all the time 1 time slot and mode 3 uses 3 time slots if each group has at least 1 user). This result confirms the fact that mode 2 offers best performance than other modes. When the system has 16 users, the conventional LCG method do not allow to transmit any bit. This result shows the interest of gathering users in groups according to their channel conditions.

VII. Conclusion

In this paper, we have jointly used linear precoded OFDM modulation technique and the conventional multicast approach to exploit the channel frequency selectivity experienced by each user in multicast OFDM systems in indoor PLC context. To increase the multicast bit rate, a new resource allocation algorithm has been proposed and different modes of gathering multicast users have also been analyzed. It has been shown through simulations that the proposed algorithm offers a significant bit rate gain compared to the conventional multicast resource allocation method. In addition, the interest of gathering multicast users into different groups has been shown.

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